



Search for the Standard Model Higgs boson in the \cancel{E}_T plus jets sample

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We search for the Higgs boson produced in association with a Z or W boson. We consider a scenario where $Z \rightarrow \nu\nu$, or $W \rightarrow l\nu$ and the lepton escapes detection; the Higgs boson decays into a $b\bar{b}$ pair. The acceptance has been drastically increased with respect to the previous analysis by releasing the cuts on jet E_T 's and number of jets, and implementing a NN to remove the huge backgrounds that enter as a consequence of the loosening of these cuts. We check the goodness of our background modeling by comparing data against backgrounds in many control regions, and find good agreement. An additional NN is used to discriminate the Higgs signal from the remaining background. Observing no significant excess in the data we place 95% confidence level upper limits on the Higgs boson production cross section. For a mass of 115 GeV/ c^2 the expected (observed) limit is $5.6^{+2.4}_{-1.6}$ (6.9) times the standard model prediction.

I. INTRODUCTION

The search for the Higgs boson is one of the most active areas of research at the Tevatron. The electroweak fits to SM parameters, performed including the latest Tevatron top mass averaged measurements [1], point to the value $m_H = 87^{+36}_{-27} \text{ GeV}/c^2$, or $m_H < 160 \text{ GeV}/c^2$ [2]. In the mass region above $\sim 135 \text{ GeV}/c^2$ the searches focus on $gg \rightarrow H$ where $H \rightarrow WW$, because of the high cross section and the “low” backgrounds when the W’s decay leptonically. At low mass the searches focus on the production of H associated with either a Z or a W boson. It has to be noted that while both CDF and D0 are close to exclude, or to have a first hint of the Higgs boson in the high mass region, the low mass searches are lagging behind. In fact, none of the searches in the various low mass channels are reaching sensitivity to the Standard Model Higgs cross section. Nonetheless by combining these searches from CDF and D0, the collaborations might have a chance to exclude or find a low mass Higgs boson.

This note describes a search for Higgs boson production in association with a Z or W boson in $\bar{p}p$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ with the CDF detector at the Fermilab Tevatron. We consider a scenario where $Z \rightarrow \nu\nu$, or $W \rightarrow l\nu$ and the electron or muon escape detection; the Higgs boson decays into a $b\bar{b}$ pair.

We split the data-sample into various control regions and a signal region. To avoid potential bias in the search, we test our understanding of the sample in control regions. The observed data in signal region is analyzed after all background predictions and final event selection is determined.

The CDF detector is described in detail in [4].

II. DATA SAMPLE & EVENT SELECTION

This analysis is based on an integrated luminosity of 2.1 fb^{-1} collected with the CDFII detector. The data are collected with a \cancel{E}_T plus two jets trigger [11].

Jets are reconstructed from energy depositions in the calorimeter towers using a jet clustering cone algorithm with a cone size of radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$. Jet energies are corrected to account for effects that cause mismeasurements in the jet energy such as non-linear calorimeter response, multiple beam interactions, or displacement of the event vertex from the nominal position. We further correct jet energies by reconstructing their four-momenta according to the H1 prescription [3]. Both the magnitude and the direction of \cancel{E}_T are recalculated after correcting the energies of jets.

The trigger efficiency is obtained from data and is used to scale the Monte-Carlo based signal and background samples to correct for event loss during data taking. The overall efficiency of the online event selection is parametrized by the offline corrected \cancel{E}_T and applied on the Monte Carlo samples providing a proper scaling for the simulated events.

From this inclusive dataset we select events offline with the following requirements[12]:

- $\cancel{E}_T > 50 \text{ GeV}$ to avoid trigger inefficiencies
- leading and the second leading jets are within $|\eta| < 2.0$, at least one jet is central $|\eta| < 0.9$
- leading jet $E_T > 35 \text{ GeV}$, second jet $E_T > 25 \text{ GeV}$
- $\Delta R(1^{st} \text{ jet}, 2^{nd} \text{ jet}) > 1.0$
- reject events with 4 or more jets with $E_T > 15 \text{ GeV}$ in $|\eta| < 2.4$ region.

Events passing all of the above selections are referred to as the *pretag sample*.

For the first time at CDF we accept events with three jets in this channel. The main motivation is to accept events where one of the b quarks coming from the Higgs radiates a gluon. In addition to that, we also accept WH events where the charged lepton coming from the W is reconstructed as a jet. The latter case happens when the W decays to $e\nu$ and the electron fails the CDF electron identification algorithm, but is reconstructed as a jet; or when the W decays to $\tau\nu$ and $\tau \rightarrow \text{hadrons}$. Table I shows the contributions in Signal region from WH processes in 2 and 3 jet events.

Process	All events		e, τ matched jet	
	2 jet	3 jet	2 jet	3 jet
$W \rightarrow \tau\nu$	44%	61%	2.8%	33%
$W \rightarrow e\nu$	38%	25%	0.6%	4%
$W \rightarrow \mu\nu$	18%	14%	—	—

TABLE I: Contributions to 2/3jet events from different decay modes of the W -boson in WH events

The major drawback of accepting three-jet events lies in the increase of QCD multijet production and pair produced top background; the latter background is a secondary one at this point and can be dealt with at later stages in the analysis.

As a way to get a better estimate of the event true missing energy we calculate the \cancel{p}_T^{tr} , which is defined as negative vector sum of charged particle track p_T 's. For true \cancel{E}_T events \cancel{p}_T^{tr} is highly correlated with Calorimeter \cancel{E}_T , while for QCD events with mismeasured jets it is not. Thus, \cancel{p}_T^{tr} would provide an additional handle to separate mismeasurements from real \cancel{E}_T events.

A. Tagging Algorithms

In order to improve the signal to background further, we need to identify jets originating from a b quark. We do so by employing both the SecVtx[5] and JetProb[6] b -tagging algorithms. We subdivide the sample into three orthogonal tagging categories:

- both jets are tagged by SecVtx at the “tight” operating point
- one jet is tagged by “tight” SecVtx and the other jet by JetProb tagger with $< 5\%$ probability
- exactly one jet is tagged by “tight” SecVtx

The double-tagged samples provide the most sensitivity in this analysis. In addition to that the single-tagged sample adds $\sim 10\%$ to the overall sensitivity.

B. Neural network to remove QCD

The main background in this search is the QCD production of two or three jets. We investigated the dynamic of the events in the sample, using a QCD heavy flavor Monte-Carlo simulation. Looking at a large set of variables, we keep here only the ones for which QCD has a very different behaviour with respect to the signal and the remaining backgrounds; the idea is that we will *remove* events very much not signal-like with a NN, and then use a second NN to *discriminate* the surviving, more signal-like backgrounds.

We train a mixture of 50% WH events and 50% ZH events against QCD heavy-flavor Monte-Carlo simulation, where we took the Higgs MC samples corresponding to $M_H = 115 \text{ GeV}$. The QCD

Monte-Carlo is used *only* for the NN training, while everywhere in the analysis we use a data driven technique (described below) to estimate this type of background.

We use the Multi Layer Perceptron (MLP) which is a simple feed-forward network, as implemented inside the TMVA [9] package. We will refer to the output of this NN as *QCD_NN*.

The variables used in the training are:

- Maximum of the difference in phi between two jets directions, taking two jets at the time;
- Maximum of the difference in the R space between two jets (as above);
- Minimum of the difference in ϕ between the missing transverse energy and each jet, considering all two or three (\cancel{E}_T, j_i) pairings;
- Minimum of the difference in ϕ between the \cancel{p}_T^{tr} and the jets, considering all two or three (\cancel{p}_T^{tr}, j_i) pairings;
- Absolute amount of the missing transverse energy, \cancel{E}_T ;
- Absolute amount of the missing transverse momentum, \cancel{p}_T^{tr} ;
- Scalar sum of transverse energy of the leading jets, H_T ;
- Ratio of missing H_T (vector sum of tight jet E_{Ts}) and missing transverse energy;
- Difference in ϕ between missing transverse energy \cancel{E}_T and missing transverse momentum \cancel{p}_T^{tr} , $\Delta\phi(\cancel{E}_T, \cancel{p}_T^{tr})$.

We use the output of this NN to define the final signal region.

III. SIGNAL AND BACKGROUND MODELING

A. Signal Modeling

The signal Monte Carlo samples are generated with Pythia [7] and reconstructed with CDF-software version 6.1.4mc set to realistic (run-dependent) mode. The ZH/WH processes were generated for Higgs boson masses ranging from 105 GeV to 150 GeV in 5 GeV steps. The cross-sections are corrected for NNLO effects by a k-Factor of 0.99 in case of ZH production and 0.96 for WH production[13]. In these samples the Higgs is forced to decay into b-jet pairs, the Z-boson to neutrinos or a pair of charged leptons, and the W decays to leptons. We use $\text{Br}(Z \rightarrow \nu\nu) = 0.200$ $\text{Br}(Z \rightarrow ll) = 0.03$ and $\text{Br}(W \rightarrow l\nu) = 0.324$.

B. Background Modeling

In the signal events the Higgs decays into two b-jets, the Z-boson into two neutrinos, and the W to leptons. The most important characteristics of these events are the large intrinsic missing transverse energy, relatively low jet multiplicity, and the lack of (detectable) isolated leptons. There are numerous Standard Model processes that can produce this signature. In this section, we list all the backgrounds considered in the analysis.

The most significant background at the first stage of the analysis is the QCD multijet processes. QCD jet production has a large cross-section ($\sim \mu\text{b}$), which is about 9 orders of magnitude greater

than the signal before requiring the first b-tag. Although, these processes generally do not have intrinsic \cancel{E}_T , mismeasured jets do cause imbalance in the total transverse energy by which the QCD events can pass the basic selection cuts if one of the jets is mis-tagged. Furthermore, QCD b-quark pair production yields taggable jets and if one b undergoes a semi-leptonic decay large \cancel{E}_T . In both cases, the missing transverse energy tends to be aligned parallel or anti-parallel to the first or second most energetic jet. This topology provides us one of the most effective devices against the QCD background.

To estimate the QCD background from data we have developed a Tag Rate Matrix (TRM) method. This allows us to estimate not only heavy flavour QCD production, but also processes with a light flavour jet falsely tagged as a b-quark. Both of these backgrounds are treated together in the following and are referred to as “Multijet”. In order to estimate the Multijet background in the single-tagged sample we measure the probability to tag one jet from the “pretag” sample (Sec. II). Similarly, to estimate the Multijet background in the double-tagged samples we measure the probability to tag a jet in a sample that already has one jet tagged. The tag rate probabilities are parameterized as a function of:

- transverse energy of the jet
- pseudorapidity of the jet $|\eta|$
- event H_T , which is defined as a scalar sum of all jets in the event
- jet Z , which is defined as a ratio of the sum of good quality tracks in the jet to the jet p_T . This quantity provides a handle to separate light flavor jets from heavy flavor jets.

The matrix is measured in subsample of \cancel{E}_T +jets dataset, which is orthogonal to the final signal sample, and is defined with the following selections:

- QCD sample
 - All leptons are vetoed using loose lepton identifications
 - Azimuthal angular separation $\varphi(2^{nd}jet, \cancel{E}_T) \leq 0.4$
 - $50 \text{ GeV} < \cancel{E}_T < 70 \text{ GeV}$

The rest of the backgrounds are determined with Monte-Carlo simulation using Pythia [7].

Two classes of top-production are considered in this analysis: the pair-production and the single top-production in the t- and s-channels. They both yield a significant contribution to the background in the signal region. Due to the large mass and the semi-leptonic decay of the top, these events are energetic, bear large \cancel{E}_T and high jet multiplicity. In the di-boson samples, the bosons’ decays are inclusive. In the W/Z + jets samples, the bosons are forced to decay into leptons, or b-quarks. The electroweak backgrounds thus include the following processes: W to leptons + h.f., Z to leptons + h.f., WW/WZ/ZZ inclusive decays.

We check our modeling of the data-sample for all tagging categories in 3 control regions which are defined below.

C. Multijet Background Normalization

In order to estimate the backgrounds originating from QCD heavy flavor multijet production, as well as falsely tagged light flavor jet production, we use the TRM method described above. This method provides us with an excellent model describing the shapes of the backgrounds very well. The normalization of the expected background is not well predicted, and a scaling factor needs to be

determined. In order to constrain the expected rates of these backgrounds we utilize EWK Control Region and QCD Control Region 2 (defined below), which are kinematic regions very close to final Signal Region. We first compute the Scale Factor in both of these regions, then compute the Scale Factor for Multijet background as the error weighted average of these two measurements.

We test the Multijet background performance in terms of reproducing the shape of the observed distributions in CDF data in CR1 and CR2. In this regions the TRM prediction is normalized to (CDF data - MC bckg). Once we are confident that the shapes are well reproduced by the matrix, we extract the normalization factor as described above, and will use this SF in the final measurement.

IV. CONTROL REGIONS

In order to test our ability to predict the Multijet backgrounds we check the performance of the method in two control regions. QCD Control Region 1 is a high statistics region where we check the data-based model and evaluate the systematic uncertainties on the shapes of various kinematic variables.

Since in the Signal Region we expect backgrounds originating from events with real high \cancel{E}_T , such as W/Z +jets, $t\bar{t}$, single top production and diboson production, we test our ability to predict this types of backgrounds in another Control Region. In order to remain unbiased to our final region, we test EWK/Top backgrounds in the kinematic region similar to Signal Region, with the exception of requiring at least one lepton in the event (all events with leptons are vetoed in the Signal Region). This region is sensitive to ElectroWeak/Top processes, and is used to check the overall shapes and normalizations of the Monte Carlo predictions. It also serves as an additional (but low statistics) check of the QCD model. The double-tagged events in this control region are dominated by the top processes, which yields an additional cross-check on top.

In order to test the data-driven estimation of QCD plus mistags in a more signal-like region, we define a QCD Control Region 2. This region intends to test Multijet data-based modeling in a kinematic region which is very similar to Signal Region. This region is defined by reversing the QCD NNoutput cut to remain blind to the signal region. In summary:

- Control Region 1 (QCD Control Region 1)
 - All leptons are vetoed using the loose lepton identifications
 - Azimuthal angular separation $\varphi(2^{nd}jet, \cancel{E}_T) \leq 0.4$
 - $\cancel{E}_T > 70\text{GeV}$ ($50\text{ GeV} < \cancel{E}_T < 70\text{ GeV}$ region is used to build the Tag-Rate-Matrix for the data-based model)
- Control Region 2 (EWK/Top processes)
 - Minimum 1 loose lepton is required
 - Azimuthal angular separation $\varphi(2^{nd}jet, \cancel{E}_T) > 0.4$
- Control Region 3 (QCD Control Region 2, Signal like)
 - All leptons are vetoed using the loose lepton identifications
 - Azimuthal angular separation $\varphi(1^{st}jet, \cancel{E}_T) \geq 1.5$, $\varphi(2^{nd}jet, \cancel{E}_T) \geq 0.4$, $\varphi(3^{rd}jet, \cancel{E}_T) \geq 0.4$
 - $QCD_NN < -0.5$ to have a high statistics sample where to check the data modeling and to extract the multijet normalization scale factor

The region with $-0.5 < QCD_NN < 0$ is kept to serve as a cross check of the multijet normalization.

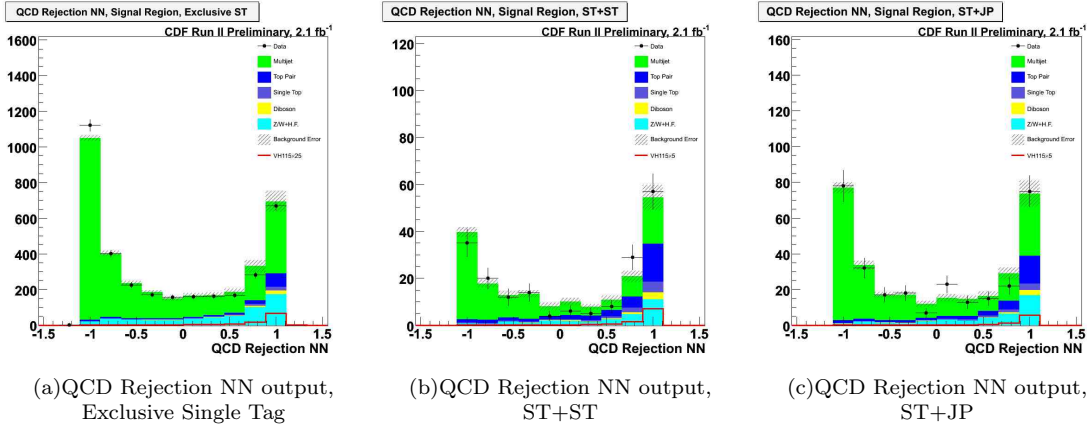


FIG. 1: QCD Rejection Neural Network output

- Signal Region

- All leptons are vetoed using the loose lepton identifications
- Azimuthal angular separation $\varphi(1^{st}jet, \cancel{E}_T) \geq 1.5$, $\varphi(2^{nd}jet, \cancel{E}_T) \geq 0.4$, $\varphi(3^{rd}jet, \cancel{E}_T) \geq 0.4$
- $QCD_NN > 0$

Comparisons of kinematic distributions in all Control Regions and in the Signal Region in all tagging categories are shown at CDF public web-page, accessible from:

<http://www-cdf.fnal.gov/physics/new/hdg/hdg.html>

Table II lists the expected and observed event yields in Signal Region.

Process	Exclusive 1Tag	ST+ST	ST+JP
QCD + Mistags	941 ± 44	42.1 ± 8.7	78 ± 11
Single Top	43.2 ± 7.9	8.5 ± 1.7	7.2 ± 1.5
Top Pair	124 ± 17	27.4 ± 4.3	27.1 ± 4.6
Di-boson	35.6 ± 6.8	4.9 ± 1.2	4.3 ± 1.1
W + h.f.	297 ± 130	11.0 ± 6.5	21 ± 11
Z + h.f.	107 ± 46	10.8 ± 5.0	11.3 ± 5.2
Total Exp	1548 ± 146	105 ± 13	149 ± 17
Observed	1443	105	148
$ZH \rightarrow \nu\nu bb$ (MH115GeV)	2.1	1.0	0.8
$WH \rightarrow (l)\nu bb$ (MH115GeV)	1.8	0.9	0.7
$ZH \rightarrow (ll)bb$ (MH115GeV)	0.09	0.04	0.03

TABLE II: Number of expected and observed events in the Signal Region in all tagging categories.

V. THE SEARCH FOR THE SIGNAL

As mentioned above, we selected the Signal Region to maximize signal significance keeping high signal efficiency. The biggest background rejected is QCD events faking high \cancel{E}_T . The dominating

backgrounds at this point are QCD, mistags, W/Z+jets and $t\bar{t}$ in similar proportions. We study the dynamic of those events to develop a NN with the goal of discriminating the surviving backgrounds from the interesting signal.

A. A second NN to discriminate the signal from the backgrounds

Since the background composition is different in events with 2 or 3 jets, we train separate Neural Networks in each category. The outputs of these networks are combined in the end, when searching for the signal. For the NN training of 2-jet events we use a background sample made of 75% of MET+JETS untagged data (none of the jets in the event are tagged) and 25% of $t\bar{t}$ events (50% – 50% mixture is used for the 3-jet NN training). The Higgs signal used for the training is a mixture of 50% WH events and 50% ZH events with $M_H = 115 \text{ GeV}/c^2$.

In order to increase the separating power of the NN, we implement the Track-based Discriminant (*trackMet* Neural Network), which was trained to optimize the separation of both ZH and WH events from QCD and $t\bar{t}$ backgrounds. A detailed description of the method can be found in [8]

The neural net chosen here is the Multi Layer Perceptron (MLP). The 6 input variables are:

- Invariant mass of all tight jets in the event: m_{jj} .
- Invariant transverse mass of all tight jets and \cancel{E}_T in the event: $m_{T,jets,\cancel{E}_T}$
- Difference between the scalar sum of transverse energy of the jets and \cancel{E}_T : $H_T - \cancel{E}_T$;
- Difference between the vector sum of transverse energy of the jets and \cancel{E}_T : $\cancel{H}_T - \cancel{E}_T$;
- The output of the trackMet Neural Network
- Maximum of the difference in the R space between the directions of two jets, taking two jets at the time;

Fig. 2 shows the NN output which we will use to scan for the presence of a signal.

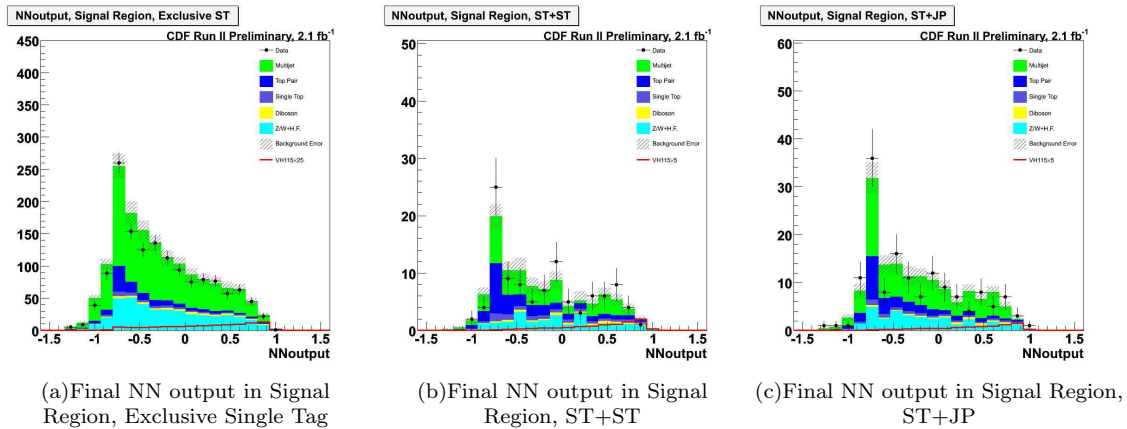


FIG. 2: NNoutput distribution in Signal Region

B. Systematic Uncertainties

The systematic uncertainties are classified as correlated and uncorrelated errors considering the relations between the signal and the background processes. The correlated errors are taken into account separately for each processes in the limit calculation. The uncorrelated systematic uncertainties are: QCD multi-jet normalization (5.5% in single tagged, 20.6% in SecVTX+SecVTX, 15.6% in SecVTX+JetProb samples), MC statistical fluctuations. Additionally, the statistical variations in TRM, which is used to estimate the multijet background, can also modify the distributions. It is taken into account by varying the TRM probability in each bin of the matrix by $\pm 1\sigma$, and the alternative shapes are used in the limit calculation. The correlated systematics are: luminosity (6.0%), b-tagging efficiency scale factor between data and Monte Carlo (4.3% for single and 8.6% for SecVTX+SecVTX, 12.4% for SecVTX+JetProb samples), trigger efficiency ($< 3\%$), lepton veto efficiency (2%), PDF uncertainty (2%) and Jet Energy Scale. ISR/FSR systematic uncertainties (between 1% and 5%) are applied on the signal.

C. Results

Considering the systematic uncertainties listed above, we computed the expected limit for the Higgs cross-section when the Higgs is produced with a Z/W boson and decays to two b-quarks where Z decays to neutrinos and W to leptons. We use Bayesian method for deriving the limits[10]. Table IV shows the final result. All the cross-sections are ratios with respect to the Standard Model cross-section.

Higgs mass (GeV)	VH limit, Combined	
	Predicted	Observed
105	$4.7^{+2.0}_{-1.4}$	5.5
110	$4.9^{+2.1}_{-1.4}$	5.8
115	$5.6^{+2.4}_{-1.6}$	6.9
120	$7.2^{+2.9}_{-2.1}$	8.9
125	$8.4^{+3.6}_{-2.4}$	11.9
130	$10.3^{+4.3}_{-2.9}$	14.4
135	$13.8^{+5.8}_{-3.9}$	16.2
140	$18.6^{+7.8}_{-5.4}$	21.0
145	$28.6^{+11.8}_{-8.2}$	33.4
150	$43.3^{+19.0}_{-12.4}$	49.8

TABLE III: The predicted and observed cross-section limits of the ZH and WH processes combined when $H \rightarrow b\bar{b}$ divided by the SM cross-section

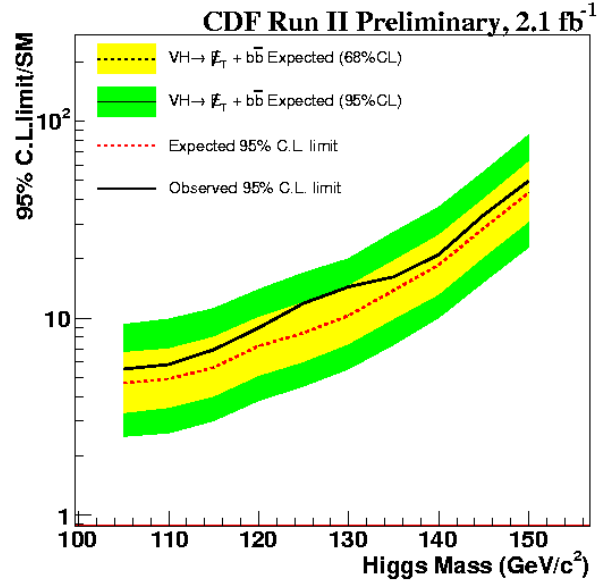


FIG. 3: 95% C.L. exclusion limits in the $VH \rightarrow METbb$ channel wrt Standard Model cross-section

Higgs mass (GeV)	VH limit, Combined	
	Predicted	Observed
105	1.5	1.7
110	1.3	1.5
115	1.2	1.5
120	1.2	1.5
125	1.1	1.6
130	1.0	1.4
135	1.0	1.2
140	0.9	1.0
145	0.9	1.0
150	0.8	1.0

TABLE IV: The predicted and observed cross-section limits of the ZH and WH processes combined when $H \rightarrow b\bar{b}$ expressed in pb

VI. SUMMARY

We have presented a search of the Standard Model Higgs boson in events $VH \rightarrow \cancel{E}_T + b\bar{b}$. A new event selection has been used to double the signal acceptance by relaxing many kinematical and topological cuts, and we now use a NN to suppress the dominant QCD background. An additional NN is used to discriminate the signal from the surviving backgrounds. We expect to set a limit on the Standard Model Higgs cross section times the branching ratio of 5.6 in the hypothesis of $M_H = 115$ GeV. In absence of a significant signal excess, we proceed to put an observed limit of 6.9, in the hypothesis of $M_H = 115$ GeV.

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